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Evaluating and comparing three community small-scale wind electrification projects

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A B S T R A C T

Electrification systems based on renewable energy have proven suitable for providing electricity autonomously to rural communities. Among the technical options available, wind systems are increasingly getting attention. In the northern mountains of Peru, at 3800 m.a.s.l., three community wind electrification projects have been implemented. The technical solutions used in each project are different: wind vs. hybrid photovoltaic-wind systems; individual equipment vs. microgrids. This study aims to describe, evaluate and compare these three small-scale community wind electrification projects. The evaluation of the three projects was carried out by comparing previous and present scenario; attention has been focused on project design and technical aspects, socio-economic impacts and sustainability and management model. These three examples shed light on both the advantages and disadvantages of different technological options as well as on appropriate community-level management models.

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1. Introduction

Early in the twenty first century, an estimated 1.4 billion people lack access to electricity and three billion people, almost half of world population, still rely on solid fuels and traditional biomass to meet their cooking needs [1,2]. Lack of electricity especially affects rural areas in developing countries, exacerbating the urban–rural division. The important role of energy systems in human development and in particular in achieving the Millennium Development Goals has been recognized worldwide [3]. Access to electricity systems would not only imply a saving to the benefiting families, but would have, among others, the following positive impacts [4,5] on: (i) providing higher-quality energy that replaces kerosene lamps and candles which produce smoke and thus can damage eyesight and lungs; (ii) extending the productive hours of the day and allowing children to do homework in the evenings; (iii) increasing access to means of communication like radios, television and cell phones; (iv) boosting the local economy by powering machinery to add value to local products, such as mills and carpentry shops; (v) improving health by refrigerating vaccines and electrifying medical devices; (vi) powering computers for schools. In particular New options for energy access may dramatic benefits for rural women which are widely in charge of collecting and managing traditional fuels [6].

The conventional strategy for increasing access to electricity is to extend the national electrical grid. Generally rural areas of developing countries are characterized by extensive and complex geography and dispersed nature of its small villages. Moreover, in many developing countries even where grid electricity is available, supply is often erratic and of poor quality [7]. For these reasons the extension of the national electrical grid to reach all rural households would be economically prohibitive and technically inappropriate [5,8]. Under these circumstances, electrification based on renewable energy has proven suitable for providing decentralized electricity to isolated communities around the world [5,9–15]. These stand-alone systems are often much cheaper than grid extension. Moreover, one of their main advantages is that they use local resources and avoid external dependences, which in turn, promotes the long term sustainability of the projects. In particular, the potential for mini-grid and off-grid technologies is expected to be high in Latin America due to the high costs of grid electrification at low population densities [16].

Among the technical options available, power systems based on micro hydro, and photovoltaic (PV) systems are the most widespread for rural electrification in developing countries [4]. Wind systems are recently receiving increasing attention [17,18]. In windy areas, the ratio investment/produced energy can be significantly reduced compared with PV systems and, moreover, wind turbines can be locally manufactured thus promoting local enterprise development and make easier the wind turbine maintenance [19,20].

Most wind electrification projects consist of the installation of only one turbine [21,22], even though they are community projects. In most of these projects the wind turbine supplies electricity to the residents of the community through battery charge services. Very few projects have used more than one turbine [23]. In Argentina, a significant institutional effort has been carried out for developing rural electrification projects in Patagonia in the province of Chubut [24] where a number of wind turbines were installed in rural households and village schools. In Peru, three projects that use wind power to electrify isolated communities have been implemented: El Alumbre [25], Campo Alegre and Alto Peru. The three communities are located in the northern mountains of Peru at 3800–4000 m.a.s.l. The technical, social and management solutions used in each community are different. In terms of power source, two communities use only wind energy whereas another uses hybrid wind and solar energy; two communities use individual home systems whereas another feed households with microgrids. The management model is designed considering both varying economic level of the community and technical design of the systems.

As of now, few studies have been published setting out empirical evaluation of electricity provisions in terms of improving living quality in rural areas of developing countries. Kirubi et al. [26] analyzed a case study dealing with a community-based electric PV microgrid in rural Kenya; they proved that access to electricity contribute to rural development, improving the productivity per worker and the productivity of agricultural activities. Kanagawa and Nakata [27] revealed quantitatively relations between access to electricity and advancements in socio-economic condition in rural areas of developing countries thanks to an energy-economic analysis carried out in grid and PV projects in India. Daka and Ballet [28] evaluated the impact of rural electrification on the children's education in Madagascar. The project area was close to an urban zone and electricity was generated with diesel motors. They established that the electrification of households affect the ability of children to keep up with their education, notably by allowing them to do their homework in the evening. Zhang and Kumar [29] analyzed a large scale rural electrification program in China, highlighting weaknesses and strengths in solar, wind and geothermal projects. Giannini-Pereira et al. [15] analyzed large scale governmental program rural electrification programs in South Africa, China, India and Brazil. The general pattern is for energy to be supplied to these areas by solar panels or a hybrid system of panels plus diesel generators. The study raised quality of life of the target population principally due to: (i) the acquisition of electronic home appliances and increased leisure time; (ii) the increasing in participation in civil organizations; (iii) the increasing access to information; (iv) the acquisition of electric home appliances and a reduction in the cost of energy by substituting renewable energy to traditional sources (e.g: kerosene, candles). Spalding-Fecher [30] reported that one of the major benefits of South African rural electrification program using PV panels, but one that is not included in traditional cost-benefit analysis is the avoided health costs of fuels such as wood, coal and paraffin. A recent publication addresses diverse initiatives taken by Brazilian government to attend rural electrification in the Brazilian Amazon [31]. The results show that "the most successful projects had financed efforts to integrate the generation of electricity into local development initiatives in order to guarantee sustainability and used substantial part of funding for local mobilization and organization".

Yadoo and Cruickshank [32] compared the experiences in Nepal, Peru and Kenya of projects using microgrids powered by biomass gasifiers or micro-hydro plants. The multicriteria assessment considers technical, economic, social environmental and institutional dimension in order to explore the extent to which sustainable welfare benefits can be created by renewable energy mini-grids.

Focusing in electrification projects that mainly use wind energy, a recent study compares 2 wind electrification projects in Bolivia; using individual wind turbines to electrify each household [33]. As technical designs are the same, the study evaluates both projects in terms of relevance, efficiency, effectiveness, impacts, sustainability, coherence and facilities. In addition, the advantages of using microgrids in future projects are discussed. These Bolivian projects used commercial wind turbines. In contrast, Leary et al. 2012 [20] analyze the use of locally manufactured wind turbines in rural electrification projects in different contexts (China, Peru, Nicaragua). The study is mainly focused on technical factors, for instance meteorological or technological reliability or resilience. Although locally manufactured technology may need organizational structures to ensure local knowledge, skills, equipment and materials, which are needed to construct and maintain such systems and ensure their long term sustainability, "it is suggested that the local manufacture of wind power technology has a much greater potential than the limited circumstances in which it is currently employed".

This manuscript aims at describing, evaluating and comparing three wind generation projects implemented in the small-scale communities of El Alumbre, Alto Perú and Campo Alegre, located at the Peruvian Andes. The wind turbines used in all the projects are locally manufactured and the technical solutions used in each project are different: wind vs. hybrid photovoltaic-wind systems; individual equipment vs. microgrids. This study analyses these community wind systems in terms of design, technical and social aspects. These three examples shed light on both the advantages and disadvantages of different technological options (individual wind turbines, hybrid systems, and microgrids), as well as on appropriate community-level management models.

The rest of this paper is organized as follows: Section 2 introduces socio-economic context; Section 3 describes the projects design; Section 4 summarizes the management model; Section 5 describes projects evaluation methodology; Section 6 details the evaluation results; finally, Section 7 summarizes the conclusions.

2. Description and socioeconomic context of the communities

In Peru, an estimated 22% of the total population, and 45% of the population living in rural areas do not have access to electricity service [34]. The majority of these people live in rural areas, where the situation is even more critical; more than 67% of the rural population in Peru does not have access to electricity.

The communities of El Alumbre, Campo Alegre and Alto Peru are located in the region of Cajamarca. Cajamarca has an area of 33,317 km^2 and a population of more than 1,400,000 people, representing approximately 6% of the country; 72% of the population of Cajamarca lives outside cities. Cajamarca is one of the poorest regions in Peru; 64.5% of the population lives below the poverty line with incomes lower than the national poverty line [35]. The Human Development Index of Cajamarca is 0.540 whereas the national average is 0.598 [36]. Cajamarca has the lowest electrification rate in the country: 40.2% [35].

In the following sections the socioeconomic characteristics of the three communities are presented enhancing the differences between them. The purpose of the socio-economic study was to analyze and understand the characteristics of the families and the communities: economy, energy consumption and demand, organizational level, and the identification of individual and group capabilities. The instruments used to collect information included socioeconomic surveys of each family, interviews with local authorities and representative residents, and a focus group with the local organizations.

2.1. Area and population

Thirty-three families (151 inhabitants) live permanently in El Alumbre. In the center of the village there is a cluster of a few households, the schools and the health post which serve 4 communities. However, the rest of the population is quite dispersed; the 33 houses are spread out over 10 km^2. Campo Alegre has 20 families (100 inhabitants) permanently living in the community; the households are scattered across 15 km^2. Alto Peru has around 60 families dispersed in a very large area, around 40 km^2. The community is divided in to two areas, the high part and the low part. In the high part of the community, close to the road, there are 14 households which were chosen for the wind project due to the high wind potential in that part of the community.

The population in all three communities is relatively young; around 70% are younger than 30. The majority of the population has partially or fully completed elementary school. Very few people have secondary studies but only 5–10% of the population is illiterate (17% in Alto Peru), most of whom are women.

2.2. Economy

In rural communities of the Peruvian Andes, economy is based on subsistence agriculture (self-sufficient farming). Cattle rearing are the most important economic activity, as sale of milk and occasionally fresh cheese provides almost the only source of income. Complementary sources of income include sale of labor and selling a small portion of their agricultural products. The most common agricultural crops are: potato, barley and native tubers.

The population can be characterized by 3 types of economic divisions, depending on their income and their land: 1) deficit, which implies very low income and 0–3 ha of land insufficient for basic needs; 2) equilibrium in which income covers their basic needs and they have 4–10 ha of land and 3) surplus, where incomes exceeds their basic needs and households have more than 10 ha of land. Campo Alegre is the community with the highest economical level and the highest proportion of surplus families (30%, 30% and 40%, respectively). El Alumbre is economically in the middle; most of the families are equilibrium (21%, 52% and 27%, respectively). Alto Peru is the community with the most poverty; half of their families are deficit (47%, 23% and 30%, respectively). However, it is worth mentioning that the beneficiaries of the projects are among the wealthiest families.

In all three communities, men temporarily migrate for work. Of the total number of families, around 10% migrate to sell their labor in agricultural activities, principally on the coast or in the jungle, for 3 to 4 months from January to April. Those who migrate are the fathers and older sons of the families, leaving mothers and children at home. In Campo Alegre, there is only sporadic migration to the city of Cajamarca.

2.3. Energy sources

The principal sources of energy are candles, kerosene, car batteries and small appliance batteries. In Alto Peru there were also small diesel generators at a few households. The average expenditure on energy was approximately $4 US in Alto Peru,

$5 US in El Alumbre and $6 US in Campo Alegre before the electrification projects.

In terms of electrical appliance use, most people had battery-powered radios, and some had sound systems or cell phones (that they would charge during trips to the city). In Campo Alegre and Alto Peru there were families with TV and DVD even before the implementation of the electrification system. The estimated future energy demand was around 380 Wh per household per day considering that they will progressively buy other home appliances such as sound systems and TVs.

2.4. Community organization and leadership

The most important community leadership is the municipal representative of the village, the deputy governor, who represent the central government, and the Ronda Campesina (community patrol group). These institutions are accepted by the entire community and have the power to call official meetings. For the implementation of the project, these were the appropriate bridges between the project promoters and the population.

3. Project design

In this section, the wind resource assessment and the wind turbines used in the projects are presented.

3.1. Wind resource assessment

The three communities and belong to the Department of Cajamarca, located in the mountainous area of northern Peru. The recently developed wind resource atlas of Peru [37] has confirmed that Cajamarca is one of the areas with the highest wind resources in the country. The three communities are close to each other and are located in areas of good wind resource in Cajamarca [25].

The three communities are located in the Andes of northern Peru at 3800–4000 m.a.s.l. Throughout the year, the climate is cold, with rainfalls during the months of January–April, and strong winds during the months of July–September. The terrain is steep and there is almost no vegetation other than wild grasses. In the first visits to the project area, it was noted that the area had potentially good wind resource. An anemometer was installed in each community, on a 10 m high tower, in a flat terrain with no obstacles that might influence the measurements. Wind measurements were taken for more than a year, but the wind resource analysis was primarily focused on the months with the least wind resource in order to guarantee the systems will generate enough energy to meet the demand throughout the entire year.

Next, using specialized software and contour maps, the data measured was used to extrapolate wind speeds in the surrounding area [38]. The energy produced at each point is calculated with the power curves of the wind turbines. Fig. 1 shows the detailed elevation and the wind map of El Alumbre, Campo Alegre

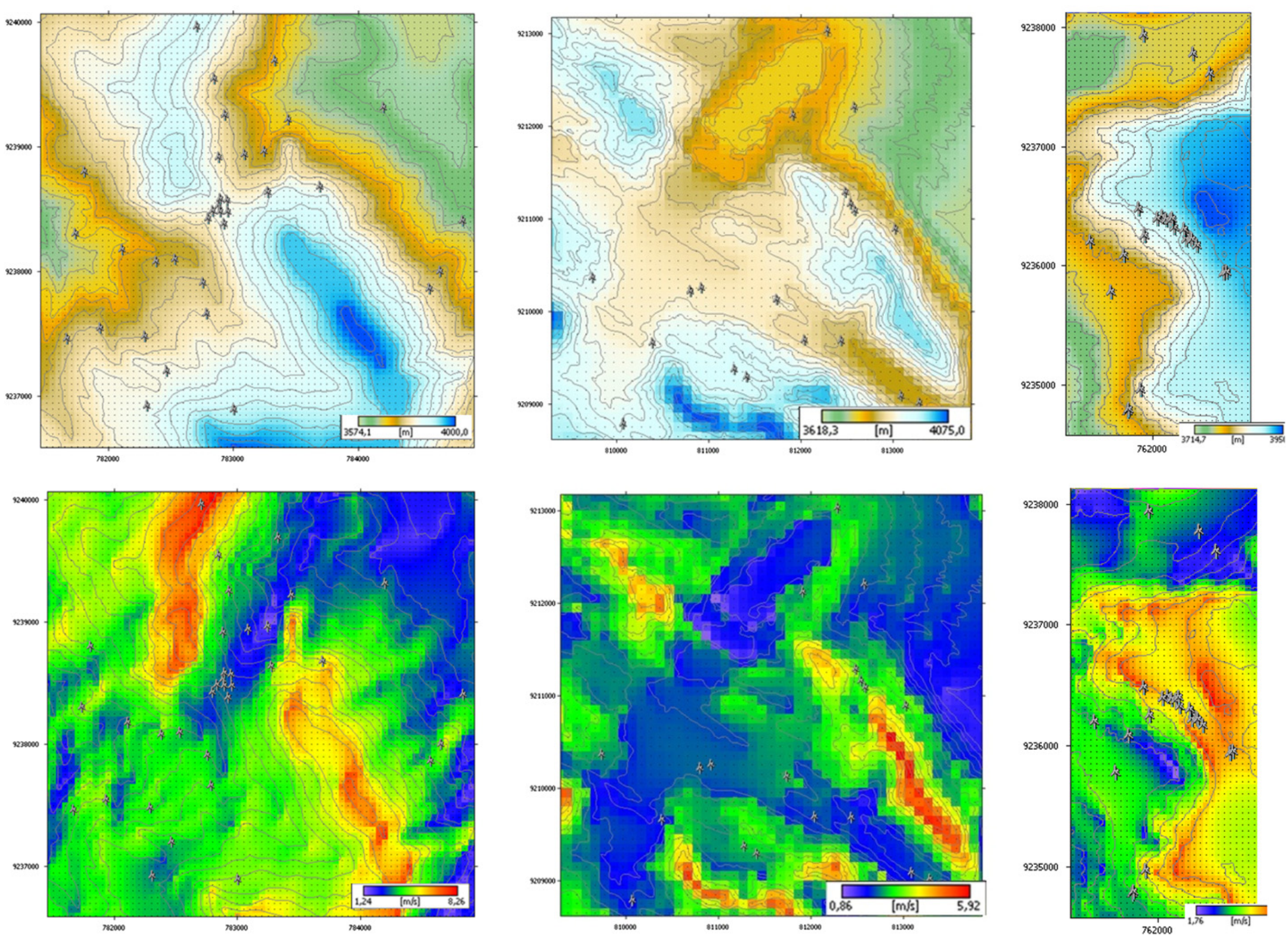

Fig. 1. Elevation (top) and wind map (bottom) of El Alumbre (left), Campo Alegre (center) and Alto Peru (right).

and the high part of Alto Peru; the location of the households is indicated. Wind resource in El Alumbre is moderate, in general. For households in the highest areas it is moderate, whereas the households in the valleys have low wind potential. Campo Alegre is the community with the lowest wind potential whereas the highest part of Alto Peru has a very high wind potential.

3.2. Wind turbines

The wind turbines, IT-PE-100 and SP-500, used in the projects are models developed by Practical Action (Peru). In 1998, Practical Action began a long-term research study focused on taking advantage of small wind energy to generate electricity for poor rural families in three countries: Peru, Sri Lanka and Nepal. In the case of Peru, the technical characteristics were defined and a number of recommendations were made: the design should use the low wind speeds that predominate in Peru and allow local manufacturing in order to ensure technical sustainability and the long-term supply of spare parts, among other considerations.

The turbines developed were specifically designed to operate at low wind speeds [25]: the IT-PE-100 operates with wind speeds from 3.5 m/s to 12 m/s, and produces 100 W at 6.5 m/s; the SP-500 operates with wind speeds from 3.5 m/s to 12 m/s, and produces 500 W at 8 m/s. Both models are furling tail turbines with 3 fiberglass blades and axial permanent magnet generators. The wind turbines are manufactured by a local company in Lima, thereby stimulating business creation and facilitating repair and parts replacement. These designs prioritize durability and ease of maintenance, essential for project sustainability.

3.3. Technical description of the projects

3.3.1. El Alumbre

The electrification project was designed to cover basic household needs and community services (school and health center) using individual systems: 33 wind turbines of 100 W (IT-PE-100) were installed at households and wind turbines of 500 W (SP-500) were installed at the school and the health center. At each point of consumption, the equipment installed included a controller, some batteries and an inverter to facilitate the purchase and use of AC equipment.

The project was implemented in two phases. In a first phase, in January 2008, 21 wind turbines of 100 W were installed in 21 homes and a wind turbine of 500 W was installed in the school. In a second phase, in January 2009, 12 more family systems and a 500 W wind turbine were installed to electrify homes and the health center, respectively. In the first phase, turbines were installed on towers 7 m high. Due to the lack of wind resource, and thus energy at some points, several 7 m towers were changed to 10 m towers to reach the higher wind resources. The turbines of the second phase were directly installed on 10 m towers.

This project was promoted by the NGOs Practical Action from Peru (PA-Peru), Engineering Without Borders – Catalonia from Spain (EWB-Spain), and Green Empowerment from USA (GE), with support from the Technical University of Catalonia (UPC). To our knowledge, the project in El Alumbre has been the first experience of micro wind electrification projects in mountainous areas, using individual wind turbines at each family household, and it was the first small-scale community wind generation project for rural electrification in Peru.

3.3.2. Campo Alegre

The electrification project was designed to cover household needs using individual systems. A wind turbine of 100 W (IT-PE-100) and a solar PV of 50 W were installed in 20 households. At each point of consumption, the equipment installed included a controller and a battery bank. No inverters were included so the power supplied in households is DC. The installation of the systems was done in March 2008. This project was promoted by the Ministry of Energy and Mines of Peru, and was implemented and developed by PA-Peru.

3.3.3. Alto Peru

The wind electrification project covers the needs of the households close to the road and some small commercial use. The electricity is distributed using two independent microgrids; each microgrid is fed by two wind turbines of 500 W (SP-500). In this project the use of microgrids was implemented instead of individual generators, significantly reducing the initial investment cost. At each point of generation, the equipment installed included a regulator, a battery bank and an inverter. At each point of consumption, meters have been installed to control and register the energy consumed. The installation of the systems started in July of 2009. This project was promoted by the NGOs PA-Peru, EWB-Spain and GE, with support from UPC in the design of the project [39].

3.4. Installation

The population actively participated in the entire process of equipment installation (Fig. 2): preparation of the holes for the base of the towers, installation of the towers, construction of the control panel, and internal wiring of the households. The entire community contributed and worked during all installation process.

4. Management model

A common challenge in isolated electrification systems is guaranteeing the long-term sustainability of the projects due to insufficient maintenance or access to replacement parts. To overcome this,

Fig. 2. An individual wind turbine in El Alumbre (left) [25], and individual hybrid system in Campo Alegre (center) and a wind microgrid in Alto Peru (right).

the project organizers focused on the development of an appropriate management model.

The management model designed takes into account the internal social relations of the community, its forms of organization, values, and group and individual capabilities. To achieve sustainability of the system, the management model is based on three key points: create a micro enterprise to manage the services, strengthen the capabilities of the residents and assure commitment and participation of the population. The management model is composed by different components and actors including the micro enterprise, the users committee, the municipality and the promoter NGO [25].

4.1. Micro-enterprise

In each of the three communities a local micro-enterprise was formed to operate, maintain and administer all of the systems. In order to guarantee an efficient operation and administration of electrical service, the management must be independent of the interferences of political or personal interests. The formation of the small business promotes an entrepreneurial culture and provides local technical assistance when minor breakdowns occur. The micro enterprise is legally registered, maintains a written service contract with the users and has a tariff structure. Organizers introduced the concept that energy generation and distribution is a service to the users, and thus should be paid for.

Taking advantage and developing the existing local skills were goals of the project and were key aspects to guarantee technical and management sustainability. Thus, it was decided that the micro enterprise would be composed of one or more of the residents of the community, selected and trained to take over the operation and maintenance of the systems. First, the community itself nominated candidates to run the micro enterprise in an open meeting. Then, all of the candidates participated in a comprehensive training program which covered both administrative and technical skills, such as basic accounting and electrical wiring [40]. The advantages of training more than the selected operator-administrator is that it contributes to a fair and transparent process, and also builds the capacity in more than one person so that other people will be able to step into the management role in the future. At the end of the training workshops, the participants completed a written test on the basic concepts. Then, a committee composed of community leaders and the project organizers compared candidates based on test scores as well as criteria such as past community involvement and reputation within the community. The top candidate was selected to be the operator-administrator and a back-up person was selected to provide assistance.

4.2. Tariff and reserve fund

The micro enterprise is in charge of collecting a monthly tariff paid by the users that goes to a reserve fund and serves to cover the costs of maintenance and replacement of the equipment throughout the lifespan of the project. The tariff also serves to provide a small stipend (around $US 10/month) to the operator-administrator that incentives to provide quality service. The reserve fund is kept in a bank in the closest city and requires 3 signatures to access: the micro enterprise operator-administrator, a community authority and an energy user. The micro enterprise combines the benefits of small businesses with the values of community participation.

In El Alumbre and Campo Alegre, each family pays the same monthly amount of money, around $3 in El Alumbre and $5 in Campo Alegre. In Alto Peru, there are meters in each household and families pay depending on their consumption; these avoid conflicts in the amount of energy consumed by each family. Families pay $4 up to 10 kWh, and $0.33 per kWh until 15 kWh and $1 per kWh thereafter; the basic tariff is fixed to cover the maintenance and after that the cost increases to manage and control the consumption. So far, most of the families pay the minimum fee. This is less than the average expenditure that the families were using for energy (candles, kerosene, etc.).

4.3. Municipality

The legal owners of the systems are the municipalities. The municipality signs a concession contract assigning the service management to the micro enterprise, thus it cannot interfere with the day-to-day operations such as setting the tariff. However, as legal owners, the municipality shares the responsibility of replacing equipment in the long run to complement the community's reserve fund. The municipality also has the right to move the systems to another community if the national electrical grid should eventually arrive to the community. Finally, the project organizers supervise the functioning of the system and support the other local actors. Thus, there is a system of checks and balances which stimulate efficient and fair management of the electrical services.

4.4. Users committee and community participation

The users committee (composed of the entire community) has the right of financial review meetings every 3 months. Furthermore, periodically the community will evaluate the performance of the micro enterprise and re-elect the current, or a new, operator-administrator to run the micro enterprise.

It is critical to promote the active participation of the beneficiaries, representatives and community leaders in the entire process of project implementation. The implementation of the management model developed in parallel to the installation of systems, and promoted active participation of beneficiaries, representatives and community leaders. In the project identification phase, meetings were held with all of the beneficiaries to explain in detail the advantages and limitations of the energy systems as well as their rights and responsibilities so that the energy supply is maintained. These responsibilities include the active participation in the installation of the system and a commitment to pay a monthly tariff to guarantee the maintenance and replacement of the equipment.

Users were trained on both technical and administration topics; how to operate the household equipment, understand the regulator, manage battery charging and understand their rights and responsibilities. A training program included education for all the population on the proper use of energy, such as the use of energy efficient light bulbs and prohibition of irons or other equipment that would not work with the system. The theoretical lessons took place at the school and the hands-on practice was undertaken during the systems installation.

5. Methodology for projects evaluation

The evaluation of the projects of El Alumbre, Campo Alegre and Alto Peru was undertaken by the NGOs PA-Peru, EWB-Spain and GE, and by the UPC. In general, the purpose of an assessment is to make an evaluation, as systematic and objective as possible, of an on-going or completed project [33,41]. Evaluation tries to determine the fulfilment of objectives, developmental efficiency, effectiveness, impact and sustainability.

Different methods have been used to evaluate rural electrification projects in developing countries. Camblong et al. [5] evaluated

a micro-grid project for rural electrification in Senegal using a survey and interviews. In this case, the survey and interviews were carried out in a representative sample of the population both in non-electrified villages and electrified villages. Three kinds of surveys were developed: (i) the village surveys, which allow better understanding of the socio-economic context of the villages, were carried out by interviewing people chosen by the chief of the village; (ii) the household surveys to collect data concerning domestic behaviors related to energy consumption were directly administered to the heads of families; (iii) the technical surveys consisted of an inventory of the equipment performance (generator set, millet mill, etc.), and collecting GPS geographical coordinates of significant infrastructure such as schools, health centers or wells. Ilskog and Kjellstrom [42] evaluated seven rural electrified areas in Eastern and Southern Africa by means of: (i) interviews with management, staff, case facilitators; and electricity clients; (ii) inspections of physical assets; (iii) and reviews of available written documentation for each community included in the study. Zhang and Kumar [29] analyzed the problems encountered during the progress of a rural electrification program in rural western China. A survey was carried out at representative townships and households in three different categories: (i) village power systems; (ii) users of renewable energy power systems, and (iii) power companies and the local utility service. Wamukonya and Davis [9] carried out comparisons among grid, solar and unelectrified households by means of questionnaires and interviews. Three different questionnaires were used: (i) one for grid-electrified, (ii) one for solar-electrified and (iii) another for unelectrified households. While the basic structure of each questionnaire was the same, special questions were asked which were not relevant to the entire sample. In summary, evaluations of rural electrification projects around the world combine participatory surveys with technical reviews to access the impact of energy projects.

In this study the evaluation of the three projects was carried out by comparing previous and present scenarios, in order to analyze the achievement of the objectives established in the three projects [41]. Since energy access is linked to quality of life in rural households, social, economic and technical aspects have been considered [32]. Table 1 shows the objectives and sub-objectives of the projects and the indicators taken into account for the evaluation. Three main areas have been considered (Table 1): (i) project design and technical aspects; (ii) socio-economic aspects and (iii) sustainability and the management model.

The analysis was both qualitative and quantitative. The specific methodology consisted of (i) surveys, (ii) monthly observational visits and (iii) focus groups. The surveys of the beneficiaries of the three communities were carried out by sociologists and technical staff. The survey focused on social, economic and technical aspects of the projects. Personnel of the educational and health centers, along with municipal representatives were also involved. The information gathered in the surveys was primarily quantitative. Monthly visits on field were carried out since the beginning of the project with the purpose of reviewing the systems and supervising the use of batteries, controllers and other accessories. The generation of electrical energy was evaluated and households were surveyed to see if their energy needs were being met. The visits also focused on the social aspects of the project and strengthening of the management model. The information obtained in this case was mostly qualitative. Participatory workshops and focus groups involved leaders of the communities and local organizations, as well as authorities from government.

Table 1
Objectives and indicators for the evaluation of rural electrification projects in El Alumbre, Campo Alegre and Alto Peru (Peru).

Aspects	Objectives		Sub-objectives		Indicators	
Project design and technical aspects	OPDT1	Design	–	Ensuring simple design	IPDT1	Wind/hybrid systems, home systems and/or microgrids
	OPDT2	Energy	–	Ensuring constancy of energy services	IPDT2	Wind and solar resources constancy during seasons and at different community's points
	OPDT3	Cost	–	Implementing low-cost system	IPDT3	Cost
	OPDT4	Equality	–	Ensuring equality distribution of energy	IPDT4	Equality of the service
	OPDT5	Security	–	Reducing shortage of energy due to breakdowns	IPDT5	Number of households feed with only more than one generator
Socio-Economic aspects	OSC1	Health	OSC1-1	Improving indoor environment	ISC1	Reduction of smoke and decreasing of eye and respiratory diseases
			OSC1-2	Improving quality of health center	ISC2	Vaccine availability and storage in refrigerator
			OSC1-3	Improving working hours in health center	ISC3	Increasing of working hours in health center
			OSC1-4	Improving health center service	ISC4	Perception of the improvement of the quality of health assistance
	OSC2	Education	OSC2-1	Improving children education	ISC5	Increasing of the hours for children education at home
			OSC2-2	Improving education quality at school	ISC6	Increasing computers and multi-media equipment use in educational institution
	OSC3	Economy	OSC3-1	Reducing family's expenses for energy	ISC7	Reduction of expenses for energy (e.g. kerosene, candles, battery)
			OSC3-2	Increasing family's income	ISC8	Small-scale business implemented or improved thanks to energy services
	OSC4	Comfort and communication	OSC4-1	Improving family's use of multi-media equipment	ISC9	Increasing use of multi-media (TV, DVD) equipment at household level
			OSC4-2	Improving family's and community's communication	ISC10	Increasing use of communication equipment (e.g. cellphones, radios) at household and communities level
Sustainability and management model	OSMM1	Tariff	OSMM1-1	Ensuring timely payment of the tariff	ISMM1	Families who pay timely
			OSMM1-2	Ensuring a convenient tariff for families	ISMM2	Perception of the tariff as a convenient fee
	OSMM2	Maintenance	–	Ensuring acceptance of operator-administrator's work	ISMM3	Good opinion about the work carried out by the operator-administrator
	OSMM3	Participation	–	Improving local community participation in management model	ISMM4	Participation of beneficiaries in communities' meetings and activities related to management model

The aim was to analyze advantages and disadvantages that affected communities' organization. In this case, the information obtained was qualitative.

5.1. Project design and technical aspects

Generally, rural electrification projects in rural communities of developing countries should be simple and low-cost [43]; moreover, they should ensure equality among users and constancy of energy service. To this end, the following objectives, sub-objectives and indicators for the evaluation have been considered (Table 1):

- Design (OPDT1)-Ensuring simple design. The indicator (IPDT1) took into account the implementation of wind vs. hybrid systems and household vs. microgrid systems. First, hybrid systems (solar and wind) design is considered more complex than stand-alone wind systems. Moreover, single home systems are characterized by simpler planning and design, whereas microgrid designs and deciding where to use microgrids is more complex. The indicator assessment in this case is qualitative and design has been classified as simple, medium or complex.
- Energy (OPDT2)-Ensuring constancy of energy services. In these communities wind resource availability is characterized by a significant fluctuation among seasons; thus, energy potential may not be constant during seasons. The indicator (IPDT2) considered the wind and solar resources maps and evaluates constancy throughout the year. The indicator assessment in this case is qualitative and energy constancy has been classified as low or high for wind systems or hybrid systems, respectively.
- Cost (OPDT3)-Implementing low-cost systems. The indicator (IPDT3) considered the initial investment cost of the project. Indicator assessment has been made qualitatively and solutions have been classified as inexpensive and expensive.
- Equality (OPDT4)-Ensuring equal distribution of energy. Energy provided by home wind systems depends on the wind resource variability that characterizes the areas where they are implemented; whereas microgrids guarantee an equal energy distribution among users. The indicator (IPDT4) in this case considered the equality of energy distribution among users. Indicator assessment has been made qualitatively and service has been classified as equal or not equal.
- Security (OPDT5)-Reducing Shortage of energy due to breakdowns. Shortage of energy provision during breakdowns is especially critical when households are only connected to a single generator (either wind or solar); thus, a breakdown implies energy provision is completely stopped. When a breakdown occurs with a wind turbine in a hybrid system or a microgrid fed with multiple generators, energy provision is reduced but not stopped, so households may still use energy for more essential needs. The indicator (IPDT5) considered the number of households fed with more than one generator. The indicator has been measured qualitatively considering a low, moderate or high number of households feed with only one generator.

5.2. Socio-economic aspects

Rural electrification projects can produce socio-economic benefits and improved quality of life [3–5]. In particular, in these three electrification projects we aimed to improve health of the community, children's education, family's income, household comfort and communication. Socio-economic aspects took into account the following objectives, sub-objective and indicators listed in Table 1:

- Health (OSC1)-Improving the indoor environment (OSC1-1). The objective and sub-objective took into account the reduction of smoke and the decrease of eye and respiratory diseases. One of the main advantages of electricity provision to poor communities is the replacement of dangerous and expensive fuels such as wood, coal and paraffin, reducing exposure to indoor air pollution [30]. The correspondent indicator (ISC1) expressed, in a quantitative manner, the percentage of families who declared that health was improved thanks to the reduction of smoke due to traditional energy sources.
- Health (OSC1)-Improving quality of the health center (OSC1-2). Families' health could improve due to the availability of vaccines, especially for children, in the community, without the necessity to go to the city. The indicator (ISC2) in this case considered the vaccine availability and storage in refrigerator. It has been assessed qualitatively. This indicator (ISC2) has been evaluated only in El Alumbre, the only community where the community health center was electrified.
- Health (OSC1)-Improving working hours in the health center (OSC1-3). As mentioned above in El Alumbre the health center was electrified. Thanks to electricity the community health center could be open during the night, improving the quality of medical assistance. The indicator (ISC3) measured, qualitatively, the increase of working hours in health center. This indicator has only been evaluated in El Alumbre.
- Health (OSC1)-Improving health center service (OSC1-4). The objective concerned the improvement of community health center in the families' point of view. The indicator (ISC4) in this case took into account the perception of the improvement of the quality of health assistance. It has been quantitatively measured, by expressing the percentage of families who agree that the quality of health center was improved.
- Education (OSC2)-Improving children education (OSC2-1). Access to education for all is one of the Millennium Development Goals [3]. The energy sources used by households can affect the achievement of these objectives. In fact it has been proven that children in a household with access to energy spend more time doing their homework [44]. The indicator (ISC5) quantitatively measured the percentage of families whose children increased hours spent for homework. This indicator has been applied only in El Alumbre, where the school was electrified.
- Education (OSC2)-Improving the quality of education at school (OSC2-2). Thanks to school electrification teachers can improve the quality of education by using multi-media equipment. The indicator (ISC6) considered the increase of computers and multi-media equipment use in educational institution. It has been determined qualitatively, taking into account if schools were electrified or not and if energy was used for computers and multi-media. This indicator has only been evaluated in El Alumbre.
- Economy (OSC3)-Reducing family's expenses for energy (OSC3-1). Rural electrification can have a significant impact on families' income [27], especially by reducing the expenses for traditional energy resources. This objective has been evaluated determining the reduction of expenses for energy (e.g. kerosene, candles, battery). This indicator (ISC7) has been assessed quantitative by the percentage of expense reduction in relation to previous expenses in traditional energy sources.
- Economy (OSC3)-Increasing the family's income (OSC3-2). Energy can be used for small-scale business in the family economy. The indicator (ISC8) took into account the small-scale businesses implemented or improved thanks to energy service.

It has been quantitatively determined, by the percentage of families who used energy for improving a business or implementing or starting a new one.

- Comfort and communication (OSC4)-Improving family's use of multi-media equipment (OSC4-1). Rural electrification projects can help to improve the use of multi-media technologies (TV, DVD) at household level, improving communication, knowledge and comfort. The indicator (ISC9) quantitatively measured the percentage of families who declared that the use of multi-media equipment at household level was increased.
- Comfort and communication (OSC4)-Improving family's and community's communication (OSC4-2). In the three communities energy was used also for communication equipment like cell phones or local radio, improving communication and participation at household or community level. The indicator (ISC10) considered the increasing use of communication equipment (e.g. cell phones, radio) at household and communities level, quantitatively expressed, as the percentage of families of the community who had increased the use of communication technologies.

5.3. Sustainability and management model

Sustainability is a key aspect to ensure success of the projects over time. Since the systems have only been installed for a few years, the current functioning of the management model was chosen as an indicator for probability of long-term sustainability. Project sustainability is determined by the appropriateness of the management model and the participation of the beneficiaries. Aspects concerning sustainability and management model took into account the following objectives, sub-objective and indicators listed in Table 1:

- Tariff (OSMM1)-Ensuring timely payment of the tariff (OSMM1-1). Tariff payment on time is indispensable to ensure the sustainability and the success of the management model, to ensure money is available for replacements and equipment maintenance when needed. The indicator (ISMM1) quantitatively determined the percentage of families who pay the tariff on time.
- Tariff (OSMM1)-Ensuring an accessible tariff for families (OSMM1-2). Families' perception about the tariff is extremely important to ensure that they are able to pay and thus to guarantee the correct progress of the management model. The indicator (ISMM2) quantitatively measured the percentage of families who considered the tariff as a fair fee.
- Maintenance (OSMM2)-Ensuring acceptance of operator-administrator's work. As mentioned above, the management model implemented in the three projects is based on a micro enterprise run by an operator-administrator. The success of the management model depends on the perception of families about the work carried out by the operator-administrator. The indicator in this case (ISMM3) has been determined quantitatively by expressing the percentage of families who had a positive opinion about the work carried out by the operator-administrator.
- Participation (OSMM3)-Improving local community participation in management model. This objective measured the level of beneficiaries' participation in management model. The indicator (ISMM4) took into account the level of participation of beneficiaries in communities' meetings and activities related to management model. It has been determined qualitatively by expressing the level of participation as low, moderate or high.

6. Results and discussion

Table 2 summarizes the comparison among the three projects in terms of design and technical aspects, socio-economic impacts and sustainability. It highlights the advantages and disadvantages of each one, detailed in the following sections.

6.1. Project design and technical aspects

In El Alumbre the project has successfully been running for 3 and half years. Wind turbines cover domestic use of electricity for an average of 5 h per day; less in days of low wind. The design of the system is simple but expensive. The households situated in the lowest parts of the community lack electricity some days in the

Table 2
Indicators and results of rural electrification projects evaluation.

Indicators		Indicator assessment	El Alumbre	Campo Alegre	Alto Peru
IPDT1	Wind/hybrid systems, home systems and/or microgrids	Simple/medium/complex	Simple	Medium	Complex
IPDT2	Wind and solar resources constancy during seasons and at different points	Low/moderate/high	Low	High	Moderate
IPDT3	Cost	Cheap/expensive	Expensive	Expensive	Cheap
IPDT4	Equality of the service	Equal/not equal	Not equal	Not Equal	Equal
IPDT5	Number of households feed with more than one generator	Low/moderate/high	Low	High	High
ISC1	Reduction of smoke and decreasing of eye and respiratory diseases	Percentage of families (%)	86	75	71
ISC2	Vaccine availability and storage in refrigerator	Yes/no	Yes	NA	NA
ISC3	Increasing of working hours in health center	Yes/no	Yes	NA	NA
ISC4	Perception of the improvement of the quality of health assistance	Percentage of families (%)	78	NA	NA
ISC5	Increasing of the hours for children education at home	Families (%) whose children spend more hours in homework	71.4	61	NA
ISC6	Increasing computers and multi-media equipment use in educational institution	Yes/no	Yes	NA	NA
ISC7	Reduction of expenses for energy (e.g. kerosene, candles, battery)	Percentage of expenses reduction (%)	75%	84%	50%
ISC8	Small-scale business implemented or improved thanks to energy services	Percentage of families (%)	7	13	43
ISC9	Increasing use of communication equipment (e.g. cellphones, radios) at household and communities level	Percentage of families (%)	79	75	29
ISC10	Families who pay timely	Percentage of families (%)	100	100	100
ISMM1	Perception of the tariff as a convenient fee	Percentage of families (%)	14	100	86
ISMM2	Good opinion about the work carried out by the operator-administrator	Percentage of families (%)	86	90	71
ISMM3	Participation of beneficiaries in communities' meetings and activities related to management model	Percentage of families (%)	57	87	71
ISMM4	Increasing use of communication equipment (e.g. cellphones, radios) at household and communities level	Low/moderate/high	Low	Moderate	High

NA: not appropriate for the community

periods of the year with low wind; this fact contributes to the inequality of the energy available and low energy constancy due to high wind resource variability.

In Campo Alegre the project has successfully been running for 3 years. The electrification project covers household needs using individual hybrid wind-PV systems. Project design in this case is complex and expensive. Wind resource in Campo Alegre is low but families do not consume all the available electricity, although they have TV, DVD and even electric fences to contain cattle. In this project, the PV panel is very useful for stabilizing and guaranteeing a minimum amount of daily generated energy. This fact guarantees equality in energy distribution and constancy in energy provision. Beneficiaries have adapted their equipments to DC power but they claim they want inverters to use commercially available AC appliances.

In Alto Peru the electrification project has successfully been running for 2 years and a half. Project design is complex but cheaper than others. Families share the stored energy and so far there have not been problems in the energy management. Although in Alto Peru only wind turbines are used to feed the system, the high wind resource and the advantages of microgrids have avoided problems of lack of electricity. While a microgrid system guarantees energy equality between users, the energy constancy due to wind variability is only moderate because it depends on solely the wind resource throughout the day and the year. Moreover, coordination among users is needed when microgrid is implemented. The energy in Alto Peru is used for lights, cell phones, and TVs. There are also now lights in two small general stores, which facilitate their operation past sundown.

The risk level of breakdowns depends on electrification technology and the intensity of wind in the area. The risk is high, moderate and low for individual, hybrid and microgrids system respectively. Moreover, El Alumbre is characterized by season with very high wind resource, increasing breakdowns risk.

6.2. Socio-economic evaluation

In the three communities kerosene and candles for lighting were used before project implementation. After the project, the consumption of these traditional energy sources decreased in different proportion according to wind or solar energy available. Around 86%, 75% and 71% of families living in El Alumbre, Campo Alegre and Alto Peru respectively, reported that health has significantly improved thanks to the decreasing of smoke from kerosene and candles in indoor environment. Moreover, in El Alumbre the health center, which serves 4 communities, was also electrified and now uses electricity for lights, a sterilizer and a vaccine refrigerator. It contributed to provide energy for vaccine storage in refrigerators and to improve the quality of medical assistance, for example by increasing the working hours of medical center. In El Alumbre the 78% of population agree that the health center has improved the quality of medical assistance.

With regards to education, 71.4% and 61% of the families of El Alumbre and Campo Alegre respectively, reported that their children have increased the hours for doing homework. In particular the hours spent for homework and literacy have been increasing by about 1–2 h (Campo Alegre) and 2–3 h (El Alumbre). In Alto Peru this impact was not evaluated, because the beneficiary families do not have children attending primary school. In El Alumbre the project aimed also to provide energy to the primary school. Energy in the school powers four computers (with electronic encyclopedias) and a DVD player for educational videos, used by 80 students from El Alumbre and neighboring communities. Energy thus contributes to broadening the access to information through the use of computers and multi-media equipment by teacher and students, improving the quality of education.

Concerning families' income, first of all, in the three communities most families (75%, 84% and 50% for El Alumbre, Campo Alegre and Alto Peru respectively) confirm their expenses for energy sources have decreased. This reflects the comparison of previous expenses of kerosene, batteries and candles with current expenses plus the electrification monthly tariff. Moreover, energy system in rural areas can generate small-scale businesses. In the three communities, there are families that are using energy in a direct or indirect way in the implementation or improvement of small business. In El Alumbre 7% of the families use energy to provide services to neighboring communities, like charging cell phones and batteries; there is also a community radio station; moreover 50% of the beneficiaries claim they are interested in implementing a store. In Campo Alegre, 13% of families have improved a small business (small store and workshops) due to energy provision, and also 50% of families would like to implement food stores. In Alto Peru the 43% of families have implemented or improved small businesses using wind energy, in particular restaurants and renting rooms. In this community 43% of families would like to open a store or to use wind energy for small-scale milk processing industry. Generally, the implementation of small business is limited by families' scarce financial resources needed for the initial investment. The percentage of small scale business implemented or improved is significantly higher in Alto Peru thanks to economic level of the beneficiaries and to the strategic location of the community, most of houses are located along the provincial road where people stop to eat and a road construction crew is renting several rooms.

All families increased the number of multi-media and communication equipment after project implementation (79% of families in El Alumbre, 75% in Campo Alegre, 29% in Alto Peru). The most common equipment used at household level are DVD, radio, lantern, cell phones, TV. Using time ranges between half hours and 4 h depending on the equipment and on energy available. Every community has increased using time of about 1–2 h per day.

6.3. Sustainability and management model

In the three communities, the energy users have continued to pay the tariff into the reserve fund. All the families in Campo Alegre and 86% of the families in Alto Peru pay on time. However in El Alumbre only the 14% of families pays the tariff on time; this is mainly people punctual dissatisfaction due to eventual technical problems and periods of lack of energy. To complement this information, a survey asking the families' opinion about the tariff has been carried out. It revealed that in all communities a high percentage of beneficiaries considered the tariff as an affordable fee (86%, 90% 71% in El Alumbre, Campo Alegre and Alto Peru respectively); even 50%, 40% and 43% of families, in El Alumbre, Campo Alegre and Alto Peru respectively, consider that the tariff is cheap.

Regarding the management model, more than 50% of users in the three communities consider that the operator-administrator of the micro-enterprise is accomplishing his tasks. However, the percentage varies in the three communities. In El Alumbre 43% of families are unsatisfied with the work of the operator-administrator, and this may be explained by a combination of factors. First, El Alumbre was the first and has been running the longest, so it is more likely to have had problems over the years. Moreover, the number of wind turbine installed is the highest; therefore the possibility of breakdowns increases. Finally, as each household is fed with only one wind turbine, an eventual breakdown completely stops energy supply, so people is more sensitive to technical problems.

The level of participation is low in El Alumbre, moderate for Campo Alegre and high in Alto Peru. This may also be explained in terms of time since projects' implementation that tends to reduce people active involvement in project management.

7. Conclusions

In Peru, three projects that use wind systems to electrify isolated communities have been implemented in three communities: El Alumbre, Campo Alegre and Alto Peru. The technical solutions used in each community were different, some communities used only wind energy whereas others were hybrid PV-wind; some systems used individual equipment whereas others used microgrids. This study describes and compares these three small-scale community wind generation projects, both in technical and social aspects. The evaluation of the three projects was carried out by comparing previous and present scenarios; attention has been focused on project design and technical aspects, socio-economic impacts and sustainability and the management model. These three examples shed light on both the advantages and disadvantages of different technological options.

From a technical point of view, the hybrid systems facilitated and stabilized the energy generation throughout the year, and prevented energy shortages. Second, the use of microgrids has advantages but the system design is more complex, so appropriate designs should be based on a detailed resource map (solar, wind). In terms of socio-economic results, beneficiaries of the three communities confirm the advantages and their satisfaction with electricity service, at households and at the community services (health center and school). Moreover, some families are already using electricity to promote small businesses and most of them are interested and have ideas to do so. Concerning sustainability, the management model design and the tariff has proven suitable so far; however occasional shortages of energy significantly affect beneficiaries satisfaction and involvement.

In sum, wind systems are an advantageous and promising electrification option, but their appropriate technical design and management model is complex. Thus, the use of structured methodologies that considers economical, technical and management factors are strongly recommended as decision aid techniques to promoters of the projects.

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